469- 201

59227 U.S. PTO
08803420

-1-

DIFFUSE SURFACE INTERFERENCE POSITION SENSOR

BACKGROUND

The present invention relates to the detection of lateral position of a surface by measuring relative
5   displacement of that surface.

In the field of optical encoders, very fine resolution of relative displacement can be obtained through interferometry. A precision diffraction grating on the surface is illuminated with one or two beams from a
10   common laser source. Reflected or transmitted diffracted light interferes to create a fringe pattern, the position of which corresponds to the position of the surface. If the fringe pattern is detected as respective sine and cosine signals, direction of movement of the surface can
15   also be detected. Such a system is presented in U.S. Patent 5,486,923 to Mitchell and Thorburn.

Prior interferometric position sensors have required that the grating be positioned on the moving surface. To thus affect the measured surface may be undesirable.
20   Further, the grating must be aligned with the sensor system with great precision, a requirement which greatly complicates assembly.

Attempts have been made to use laser techniques to detect lateral displacement of a diffuse surface without
25   the requirement for a diffraction grating. For example, encoders based on the correlation of speckle patterns have been suggested by Yamaguchi et al., "Linear and Rotary Encoders Using Electronic Speckle Correlation," Optical Engineering, December 1991, Volume 30, Number 12. An
30   interferometric approach has been suggested by Hercher et al. in "Interferometric Measurement of In-plane Motion," Optical Testing and Metrology III: Recent Advances in

Industrial Optical Inspection, Proceedings of the Meeting, San diego, CA, July 8-13, 1990; Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1990, pp. 602-612. Both systems rely on the generally random phase

5   shifts of coherent radiation scattered from a diffuse surface.

SUMMARY OF THE INVENTION

The prior speckle pattern diffuse surface encoder has lacked the resolution that is often required. The prior

10   diffuse surface interferometric approach, on the other hand, is sensitive to nonlateral motion and position such as roll and standoff distance along an axis normal to the surface.

In accordance with the present invention, a position

15   sensor comprises a source of coherent illumination which illuminates a diffusely scattering surface, the motion of which is to be measured, with first and second input beams. The input beams are angled toward the surface forwardly and rearwardly relative to surface motion.

20   Optics direct light, scattered from the surface in forward and rearward directions relative to surface motion, to a fringe detector to form a fringe pattern in the plane of the detector. Movement of the surface is detected by the fringe detector through movement of the fringe pattern.

25   Illumination of the diffusely scattering surface by separate input beams from forward and rearward directions, and, in the reflective case, the detection of backscattered light from each beam, minimizes sensitivity to movement of the surface in a direction normal to the

30   surface. Backscattered light is that which, when projected onto the plane of incidence of an input beam, is substantially colinear with the input beam. Most

preferably, the backscattered light is in the same plane as and is colinear with the input beam.

In order to minimize sensitivity to roll, it is preferred that the input beams illuminate a common spot of the diffusely scattering surface.

Preferably, in order to detect only the desired backscattered light, and not specularly reflected or scattered light from the incorrect beam, the input beams are differentiated by polarization. In one embodiment, a beam of coherent illumination is split into the separate input beams by a polarizing beam splitter, and backscattered light to the detector is filtered by a polarizing beam splitter. In another embodiment, separate input beams of coherent illumination of common polarization are directed toward the surface through a polarizing beam splitter. Light from the separate input beams is separated by polarization wave plates, and the resultant backscattered beams are applied to the fringe detector.

The preferred embodiments of the invention rely on a quasi-monochromatic laser source and are able to detect position of a stationary surface. To that end, a preferred fringe detector is an array of light sensors such as the phased array detector described by Mitchell and Thorburn.

A preferred application of the invention is that of a "push pin" sensor in a servo track writer for hard disk drive fabrication. In that application, the diffusely scattering surface is on the read/write arm of a hard disk memory system. In the past, servo tracks have been written onto the memory disks through the use of a push pin which mechanically displaces the read/write arm of the memory system. More recently, a diffraction grating has

been placed on the read/write arm to permit accurate
sensing of the position of the arm, which is then
controlled through its own voice coil motor in a servo
control loop. In accordance with the present invention,
5 the diffusely scattering surface of the read/write arm is
monitored using the optical system described above.

BRIEF DESCRIPTION OF THE DRAWINGS
        The foregoing and other objects, features and
advantages of the invention will be apparent from the
10 following more particular description of preferred
embodiments of the invention, as illustrated in the
accompanying drawings in which like reference characters
refer to the same parts throughout the different views.
The drawings are not necessarily to scale, emphasis
15 instead being placed upon illustrating the principles of
the invention.
        Figure 1 illustrates randomly phased scattered rays
from a diffuse surface.
        Figure 2 illustrates a prior art interferometer.
20   Figure 3 illustrates the speckle and fringe pattern
obtained from a 2-beam diffuse interference.
        Figure 4 illustrates aspects of the invention.
        Figures 5A and 5B illustrate a preferred embodiment
of the invention.
25   Figure 6 illustrates another preferred embodiment of
the invention.
        Figure 7 illustrates an alternative beam splitter for
use in the embodiment of Figure 6.
        Figure 8 illustrates a preferred phased array fringe
30 detector for use with the invention.
        Figure 9 illustrates a push pin application of the
invention.

Figure 10 illustrates an embodiment of the invention using a transmissive surface.

Figure 11 illustrates use of the invention to track a spindle.

5   DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

In preferred embodiments of the invention, light from a laser is focused and split into input beams which are directed to the diffuse surface. Scattered light is accepted back into the sensor and directed to a detector

10   array where an interference pattern is formed. As the diffuse surface is translated, the scattered light is shifted in phase, causing the interference fringes to translate over the detector. The resulting detector signals change in direct proportion to the lateral

15   movement of the surface. Although described below principally in terms of an opaque surface, the invention may also be applied to a transmissive surface.

To understand the basic operating principles of a diffuse sensor, begin by looking at a single coherent

20   laser beam 20 directed down to a surface 22 at normal incidence as illustrated in Figure 1. As a region of the surface is illuminated, light is scattered in virtually all directions from each point within that region. The phase of the scattered light in any particular direction

25   from any particular point could be anything between 0 and 2π, this random phase being due to the random surface roughness.

Each location in space above the surface is a meeting point for an infinite number of randomly phased rays that

30   originate from each illuminated point on the surface. Due to the coherent nature of the light, distinct speckle patterns are formed; that is, there will be constructive

interference of this energy at some locations, and
destructive interference at others, depending on the
random set of phases dealt to each point in space. The
speckle pattern comprises bright and dark randomly
5   arranged patches when viewed on a screen.

The graininess of the speckle pattern (i.e., the
sizes of the bright and dark patches) is dependent on the
size of the illuminated spot and the distance between the
diffuse surface and the viewing plane. As the illuminated
10   spot gets smaller, the speckles grow larger; viewing the
speckles farther away has the same effect. By selectively
restricting the light to a relatively small cone of
illumination, by the use of apertures or by illuminating
only a small spot on the surface, for example, there are
15   less contributors to the energy at each spot and the
speckles are larger.

Consider the scattered light from a single small spot
on the diffuse surface, a spot that comes from a narrow,
normally incident beam as in Figure 1. Light heads off in
20   all directions from that spot, and the amount of energy in
any particular direction is a function of the off-axis
angle. As the surface moves, the phase of the scattered
light is affected, and the magnitude of this phase change
is also a function of the off-axis angle. As the surface
25   moves to the right as indicated by arrow 21, the light
that is scattered to the right is upshifted, or advanced
in phase, and the greater the off-axis angle of the light,
the greater the upshift. Light scattered to the left will
be phase-shifted in an equal but opposite manner as a
30   function of angle; i.e., that light will be downshifted as
the surface moves to the right.

When the illuminated spot is larger, so that many
scattering points must be considered, all scattered rays

directed to a single point in the detection plane are
phase shifted in unison, so that for small movements the
speckle does not change much. It is the relative phase
between all of the contributors that determines the
5   speckle pattern, not some absolute phase. However, as the
surface continues to move, it becomes clear that the
speckle pattern is actually gradually changing, since
moving the surface changes the set of scattering points
that determines that speckle pattern.

10   It is important to note that increasing the speckle
size by making the spot small on the surface has the
advantage of creating speckles spatially large enough to
cover a detector, but the disadvantage of causing the
speckle to move relatively fast across the detector plane
15   for a given surface movement, since it takes very little
movement to completely change the set of scattering points
that contributes to the speckle.

If, as illustrated in Figure 2, we direct a narrow
right-scattered cone of light 24 to a detector plane 28,
20   and also direct a left-scattered cone of light 26 to the
same detector, the overlapping of this illumination
creates a more complex interference pattern on the
detector array. The result is different from a simple
addition of the individual speckle patterns. Since these
25   two "beams" can interfere with each other, and they come
together at two different average incident angles,
relatively straight interference fringes are formed within
a new speckle pattern as illustrated in Figure 3. The
fringe period is determined by the wavelength of the light
30   and the angle between the two beams; the greater the
angle, the smaller the period.

Using this optical system that combines right-
scattered light with left-scattered light, translate the

diffuse surface. The speckle pattern will change slowly as the surface is moved and the set of scattering points is altered. In addition, since one of the beams is upshifted and the other is downshifted, the relative phase

5 between the two beams changes in direct proportion to the surface motion; this relative phase change results in fringe motion. Fringes are seen moving within the speckle, as the speckle is changing its shape at another rate, a slower rate with proper selection of spot size.

10 This means that the output from the detector will consist of high modulation signals over a finite range, and then drop off in modulation as the speckle changes to a dark speckle in the detector region. Further movement of the surface will illuminate the detector with another bright

15 speckle and high contrast fringes resulting in another set of high modulation signals.

The sensitivity to motion is determined by the angles between the scattered rays and the specular reflection direction. Until now we have suggested that only the

20 angle between the scattered ray and the normal determines the sensitivity; but in our examples so far we have been considering only the case of a normal incident beam, and there the specular reflection is along the normal. The greater the angle between the specular reflection and the

25 scattered ray, the smaller the surface motion required to generate a 2π relative phase change between the beams at the detector. The 2π phase change causes the fringes to move through one cycle.

If, as illustrated in Figure 4, we use two input

30 beams 30,32 from the same source and allow the scattered light 34,36 to interfere on the detector 28, the sensitivity (i.e., the surface motion to produce one cycle of fringe motion), is determined by

Sensitivity = $(\sin(\gamma_1) - \sin(\gamma_2))/\lambda$

Where

λ = wavelength,

$\gamma_{1,2}$ = angle between specular reflection and scattered

5   ray for beams 1 (30) and 2 (32), respectively,

where the signs of the angles are positive if the scattered ray is rotated from the specular ray toward the vector which describes the surface motion and negative if the rotation of the ray from the specular ray is away from

10 the direction of the surface motion. Thus, in Figure 4, γ_1 is negative and γ_2 is positive.

We also define

$\alpha_{1,2}$ = angle between the input ray and the normal for beams 1 and 2, respectively,

15      $\beta_{1,2}$ = angle between the scattered ray and the normal for beams 1 and 2, respectively.

The specific design for the sensor can be engineered to maximize alignment tolerances and minimize the sensitivity to motions along axes orthogonal to the

20 measurement axis. For our discussion, we define our coordinate system as follows:

X-axis: The direction in which motion is to be
          measured.

Y-axis: The axis perpendicular to the x-axis in the

25   plane of the surface.

Z-axis: The axis which is perpendicular to the
          surface.

Roll: Rotation about the Y-axis.

A laser/lens assembly, not shown, generates a

30 converging beam that is split and redirected to form two input beams 30,32 that lie in the x/z plane. Z-axis

sensitivity is minimized by sampling the backscattered
light that returns along each of these two paths 30,32
taken by the incident beams, that is, where $\alpha_{1,2} = \beta_{1,2}$,
respectively. If the diffuse surface is moved away from

5 the sensor, the distance between the detector 28 and the
illuminated spots on the surface is increased, which
normally would reduce the angle between the two
interfering scattered beams and result in a larger fringe
period. But with $\alpha_{1,2} = \beta_{1,2}$, moving the diffuse surface

10 also changes the separation of the two spots, compensating
for the increased detector-to-surface standoff and
maintaining a constant angle between the scattered beams
at the detector. The result is a near constant period
which minimizes any contrast loss due to mismatches with

15 the fringe detector. In addition, maintaining symmetry,
that is having $\alpha_1 = -\alpha_2$, eliminates a phase shift error
which occurs with z-axis motion when the two input beams
reach the surface asymmetrically.

Even in the case when $\alpha_{1,2} \neq \beta_{1,2}$ the resulting z-axis

20 sensitivity can be minimized. The sensitivity to z-axis
motion depends on the symmetry of the input beams about
the normal to the surface, the magnitudes of $\gamma_{1,2}$ and the
magnitudes of $\alpha_{1,2}$. For example, with a 70 mm detector
standoff $|\alpha_{1,2}| = 2.75$ degrees and $|\gamma_{1,2}| = 0.5$ degrees,

25 there is only a minor 1.0% change in the interference
fringe period form a 1.0 mm z-axis displacement. On the
other hand, with $|\alpha_{1,2}| = 1$ degree and $|\gamma_{1,2}| = 3$ degrees
the interference fringe period will change by 5.5% for the
same displacement.

30 Roll sensitivity is minimized by ensuring that the
two input beams are focused onto the same point on the
diffuse surface. As the surface is tilted, the beams may

see a phase advance or retardation, but the two beams will
change identically. This would not be the case if the
spots were separated on the surface. Remember that it is
relative phase change between the two beams that results
5   in fringe movement. Overlapping the illuminated spots not
only minimizes the roll sensitivity, but also maximizes
the roll range over which the sensor can operate. Of
course, if the surface is moved away from the sensor in
the z-direction, the spots will separate slightly on the
10   surface and there will be some residual roll sensitivity;
but that change will be minor given the typical, limited
z-axis range (e.g., ±0.5mm), and a small angle of
incidence.

The range of y-axis motion is maximized by keeping
15   the speckle change as a function of diffuse surface
position small in that dimension. The key is to make the
speckle large enough to adequately cover the detector with
uniform, straight fringes, but also keep the illuminated
spot large enough so that many scattering points are
20   contributing to that speckle, resulting in a relatively
low rate of speckle change.

The sampling of backscattered light must be done in
such a way that the specular reflection from the opposite
input beam does not travel along that same path as the
25   desired backscattered light and find its way to the
detector. If it did, the result would be a large
amplitude subharmonic in the fringe pattern. To protect
against this, polarization filtering is employed in the
preferred embodiments.

30   In one approach illustrated in Figures 5A and 5B, a
linearly polarized converging input beam 38 is split by a
polarizing beamsplitter 40, creating two orthogonally

polarized input beams 42,44 which are directed to the
diffuse surface 22 in the x/z plane, the latter beam by
mirror 45. The scattered light is sampled off axis, as
illustrated in Figure 5B, and the two return paths 46,48,

5 one of which includes mirror 47, are polarization filtered
by the beam splitter 41. The polarization filtering
effectively blocks light of the unwanted linear
polarization, such as the specular reflection from the
other input beam. To cause the two beams to interfere at

10 the detector, a polarizer 50 can be inserted in the two
rays, or retarders can be used, one in each path just
before the detector, to convert the two beams to a common
polarization. In spite of the off-axis return path, the
sampled light is effectively backscattered colinearly with

15 the input beams since projections of the scattered rays
onto the input plane fall directly on top of the input
rays. Alternatively, the input beams could be off-axis
with the detection beams on-axis, or both could be off-
axis.

20　　　The preferred fringe detector 28 is a phased array
detector such as disclosed in U.S. Patent 5,486,923. Such
a detector is illustrated in Figure 8. The example phased
array is a linear array of detector elements 64 grouped as
quadrants of elements A, B, C and D. All elements of the

25 same letter designation are tied together to provide a
summed output, thus providing four summed outputs. The
phased array is designed to match the period of the fringe
which is to be detected, the quasi-sinusoidal fringe
amplitude being illustrated above the detector array in

30 Figure 8. Thus, in one system the optics are designed to
provide a fringe at the detector 28 having a period of 30
microns to match a quadrant length of 30 microns. Thus,
the signals detected within each quadrant are reinforced

by signals received in successive quadrants at successive
fringes. The four outputs from the detector array are
processed by the processor electronics 66 to generate sine
and cosine outputs which in turn provide high resolution
5   position and direction of movement signals.

Other detectors such as CCD arrays may also be used.
In fact, a single sensor can detect motion of the fringe
pattern. To provide position information, at least two
measurement degrees of freedom are required from the
10 detection system. In the phased array detector of Figure
8, multiple spatially displaced detector elements are used
to enable detection of position of the surface even when
it is stationary (static position). In another
configuration the input signals might be dithered in time
15 and the static position information obtained using a
single sensing element. Alternatively, from a known
position, a position can be determined by continuously
monitoring a passing fringe pattern with a single
detector, motion providing the second degree of freedom.
20 The capacity for static position sensing is particularly
important where there are significant times of no relative
movement such as in a servo control, where a null
condition is maintained, or where energy must be conserved
by pulsing the sensor on and off.

25   Another approach, illustrated in Figure 6, uses
circularly polarized light to distinguish one beam from
the other. A single slowly converging input beam 52 which
is horizontally linearly polarized is split by a prism 54
into two separate beams 53,55 diverging from each other in
30 the horizontal plane. These two are reflected downward by
a polarizing beamsplitter 56, redirected by another prism
58, pass through quarter wave retarders 60,62 and form two
small overlapped spots of light on the diffuse surface.

By orienting the optical axes of the retarders orthogonal to each other, one of the beams is right circularly polarized, and the other left. With this configuration, backscattered light from the surface will propagate back

5 through the retarders, prism, and beamsplitter and form interference fringes on the detector. Due to its polarization after passing back through the retarders, forward scattered and specularly reflected light is directed away from the detector at the polarizing

10 beamsplitter. This design is more stable mechanically, and also offers the optical stability of an equal path interferometer. It will be recognized that many other architectures based on polarization and appropriate use of retarding wave plates will provide the desired selection

15 and interference of backscattered light.

Figure 7 illustrates an alternative to the splitting prism 54 of Figure 6. This prism 54' includes angled faces at both ends to create parallel input beams 53' and 55'. Many other mechanisms for providing separate beams

20 from a common laser source are well known. For example, partially reflecting beam splitters, polarizing beam splitters, and multilevel diffractive optics may be used.

A particularly useful application of the present invention is in a servo control loop used to write servo

25 tracks on magnetic memory hard disks. In a final stage of the hard disk drive fabrication, servo tracks must be precisely written on the magnetic media. To that end, each hard disk assembly is installed in a servo writing system which controls the location of the read/write arms.

30 Such an application is illustrated in Figure 9. In the example shown, a read/write arm 70 of the hard disk drive carries three pairs of read/write heads 72. The memory disks (not shown) rotate between those pairs.

Displacement of the read/write heads across the rotating magnetic storage disks is obtained by rotating the read/write arm 70 about an axis 74 by means of a voice coil motor 76.

5   In the past, a servowriting system has included a mechanical push pin which extends through an opening in the hard drive housing and contacts the read/write arm 70. This push pin would extend from an arm 78 which rotates about a shaft 80 coaxial with the read/write arm axis of

10   rotation 74. The angular position of the shaft would be determined by a servo controlled motor which uses an encoder or other interferometer for position feedback.

More recently, the mechanical push pin has been replaced by a non-contact optical system, which eliminates

15   the distortion, resonance, and contamination problems associated with physically contacting the arm. With this system, a small diffraction grating is placed on the read/write arm 70. The servo writer arm 78 contains an interferometric position sensor that emits an optical beam

20   82 into the hard disk drive and determines the position of the read/write arm 70 by monitoring the light diffracted from the grating. Closed loop servo control of the read/write arm position with respect to the shaft is achieved using this encoder to provide position feedback

25   and the internal voice coil motor 76 to drive the arm. The angular position of the shaft is still controlled by its original positioning system.

In accordance with the present invention, the grating based position sensor is replaced by the diffuse surface

30   sensor of the present invention, and the diffraction grating is eliminated from the read/write arm. Due to the random nature of the sensor's speckle pattern, as illustrated in Figure 3, the precise location of well

defined fringes is initially uncertain. For this reason the servo writing startup procedure involves a search routine to locate an acceptable region of clearly detected fringes. Thereafter, the optical push pin arm 70 is

5 caused to remain over that region for fine servo control of the read/write arm.

An advantage of the present invention is that nothing need be attached to the object to be measured. The object need only have a finish that diffusely scatters light.

10 Acceptable diffuse scattering can generally be obtained by conventional processes such as glass bead blasting, chemical etching, and grinding. The backscattered energy can be enhanced by preparing the surface with a random linear structure oriented perpendicular to the direction

15 of motion. Compared to an isotropic random structure, this makes more efficient use of the incident light by scattering a larger portion back along the incident path. Higher backscattered energy contributes to higher signal to noise ratio, and consequently improved precision in the

20 position measurement made by the sensor. Aluminum rubbed with emery paper, and aluminum foil - which typically contains such structure - are examples of this type of surface.

Figure 10 illustrates a case of measuring position of

25 a transmissive surface. Two input beams 90 and 92 are scattered by a transmissive surface 94. Scattered beams 96 and 98 form a fringe pattern on detector 100. In the transmissive case, the equivalent of backscattered light is light which is scattered at an angle to the normal that

30 is equal to, but in a direction opposite to, the input beam angle of incidence.

While this invention has been particularly shown and described with references to preferred embodiments

thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the spirit and scope of the invention as defined by the appended claims.

5   For example, though illustrated to detect motion and position along a single axis x, with additional optics, the motion and position in other directions may also be measured.

Similarly, although the invention is particularly

10   useful in the push pin application, those skilled in the art will see its application to other non-contacting position sensing applications, such as the measurement of the rotation or angular velocity of motor spindles. For example, Figure 11 illustrates a spindle 102 mounted to

15   the rotating shaft of a motor 104. The position of that spindle 102 may be detected by a system, as described above, positioned at either 106 or 108.